May 31, 1963
DMIC Memorandum 168

SOME OBSERVATIONS ON THE ARC MELTING OF TUNGSTEN

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Contract No. AF 33(616)-7747
Project No. 2(8-8975)

SOME OBSERVATIONS ON THE ARC MELTING OF TUNGSTEN

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SUMMARY

A semiempirical approach was employed with the aid of a statistical index of correlation to develop an "adjusted melting-rate parameter" which was linearly related to, and showed a high degree of correlation with, input power during melting. Melting data for tungsten-base materials ranging in composition from 92 to 100 per cent tungsten were used in this analysis. The new parameter developed was a function of the five variables considered most important to the consumable-electrode arc-melting process, i.e., input power, melting rate, electrode density, and the ingot and electrode diameters. The linear relationship achieved from this analysis is given as follows:

$$P = 10\,R\rho\,(0.8D_e^2 + 0.2D_i^2) + 100, \text{ or } \quad R = \frac{P - 100}{10\rho\,(0.8D_e^2 + 0.2D_i^2)} \;.$$

INTRODUCTION

Consumable-electrode arc melting is already a popular process for melting a wide variety of steels, titanium alloys, and metals for nuclear applications. Currently, it is also being applied to the refractory metals tungsten, tantalum, molybdenum, and columbium, and to their alloys. Melting, as opposed to consolidation by the previously conventional powder-metallurgical process, is being considered for these metals for three main reasons:

(1) The size and quality of primary working billets for subsequent fabrication may be limited by powder-metallurgical techniques.

(2) Higher purity material is possible since, in arc melting, the mechanisms for purification are not limited by strongly time-dependent solid-state reactions.

(3) Arc melting is the most convenient means to prepare homogeneous solid-solution or heat-treatable-type alloys.

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DISCUSSION OF TUNGSTEN ARC MELTING

The general purpose of this memorandum is to discuss arc melting as it is being applied to the consolidation of tungsten-base materials. Although potentially an important process, the arc melting or arc casting of tungsten-base materials is quite difficult. This difficulty is reflected in final ingot quality. One of the major problems in this respect is ingot cracking by thermal shock. Both the steep thermal gradients that exist when tungsten-base materials are cast and the brittle behavior of tungsten at room temperature contribute to the problem of cracking. Other problems that influence ingot quality include (1) grain size and orientation, (2) the surface condition of the ingot, and (3) alloy homogeneity, which are discussed below.

(1) Without exception, the large columnar grain structure of arc-cast tungsten ingots requires high-temperature (3000-4000 F) extrusion as the primary working operation. Clearly, this process is uneconomical and could foreseeably be eliminated if arc-melting methods capable of providing uniformly fine-grained ingot structures were developed.

(2) The sidewall condition (surface quality) of the ingot is important when considering the yield of material from ingot to primary working billet. Current melting practices produce ingots requiring 1/8 to 1 inch of metal removal (from the radius) to attain a defect-free surface. Eventually, with optimized and improved melting practices, these metal losses should be minimized.

(3) The third factor, alloy homogeneity, is important because the eventual production of high-quality mill products depends on the controlled uniform distribution of alloying elements. The problems associated with ingot inhomogeneity originate mainly from improperly prepared consumable electrodes, which permit premature melting of lower-melting-point alloying additions, thereby causing alloy segregation. Using the segregated ingots as consumable electrodes, one or more remelting operations to larger size ingots are usually required to restore homogeneity.

Realizing the existing need for improved ingot quality, studies are currently in progress to advance the technology of tungsten-base-alloy consumable arc melting. Generally, the goals of these studies are to improve ingot quality by optimizing and developing more consistent melting practices. Complicating the progress in these programs, however, is the fact that little is known about the relationship between the several variables which define this combined melting and casting operation. Clearly, a relationship between

the variables would be of value, as it would provide the necessary tool for a closely controlled, systematic investigation to determine what factors predominantly influence the melting process and, more important, the resultant ingot quality.

In this respect, it is the specific purpose of this memorandum to aid the current developmental efforts by presenting a tentative rational relationship among several of the more important arc-melting variables, e.g., input power, melting rate, electrode density, and the ingot and electrode cross-sectional areas. A semiempirical approach was employed in the analysis. The procedures and results are discussed below.

ANALYSIS OF DATA

Data for the present paper were obtained from a review of current arc-melting practices being applied at seven different arc-melting facilities.[1-8]* Generally, this review was limited to direct-current straight-polarity (electrode negative) melting methods, and, as shown in Table 1, a moderately broad range of values was obtained for each variable considered important to the process. In this respect it is particularly important to note that melting data were obtained from alloy compositions ranging between 92-100 per cent tungsten. Mainly a melting point consideration (to be discussed later), it would have been desirable ideally to limit data to a single tungsten-base composition. Practically, however, this was impossible, since sufficient data for the subsequent analysis were not available for either the unalloyed tungsten or any single alloy composition.

As a first approximation, the most reasonable and convenient choice for a correlation among the arc-melting variables listed in Table 1 seemed to be one of input power (volts x amperes) versus melting rate (pounds per minute). Figure 1 represents the initial attempt to relate these variables, and although it is apparent that a relationship exists, the degree of correlation is poor.

A more exact measure of the degree of correlation shown in Figure 1 was obtained by calculating a statistical index of correlation, the rank-order correlation coefficient (r). Defined by the formula[9]

$$r = 1 - \frac{6\Sigma d^2}{n(n^2-1)} ,$$

values of r for positive correlations may range between 0 and 1 with 0 representing no correlation and 1 representing an ideal correlation. A value of 0.65 was obtained for the data shown in Figure 1.

Using the correlation coefficient as a guide, it was the objective of subsequent calculations to improve the relationship between input power and melting rate. Generally, this was accomplished by developing a new or adjusted melting-rate parameter which showed a higher degree of correlation when related to input power. Allowances were made in this new

*References are listed at the end of this memorandum.

TABLE 1. SUMMARY OF CONSUMABLE-ELECTRODE VACUUM ARC-MELTING VARIABLES

Variable	Range of Values Encountered
Alloy Composition, weight per cent tungsten	92-100
Electrode Properties	
Density, per cent of theoretical (ρ)	70-100
Diameter, inches (D_e)	0.75-2.25
Ingot Properties	
Weight, pounds	7-84
Diameter, inches (D_i)	2.50-5.00
Melting Conditions	
Amperes	2700-8000
Voltage	22-36
Input Power, kilowatts (P)	87-247
Melting Rate, pounds per minute (R)	0.25-2.47
Vacuum, microns Hg	0.02-50

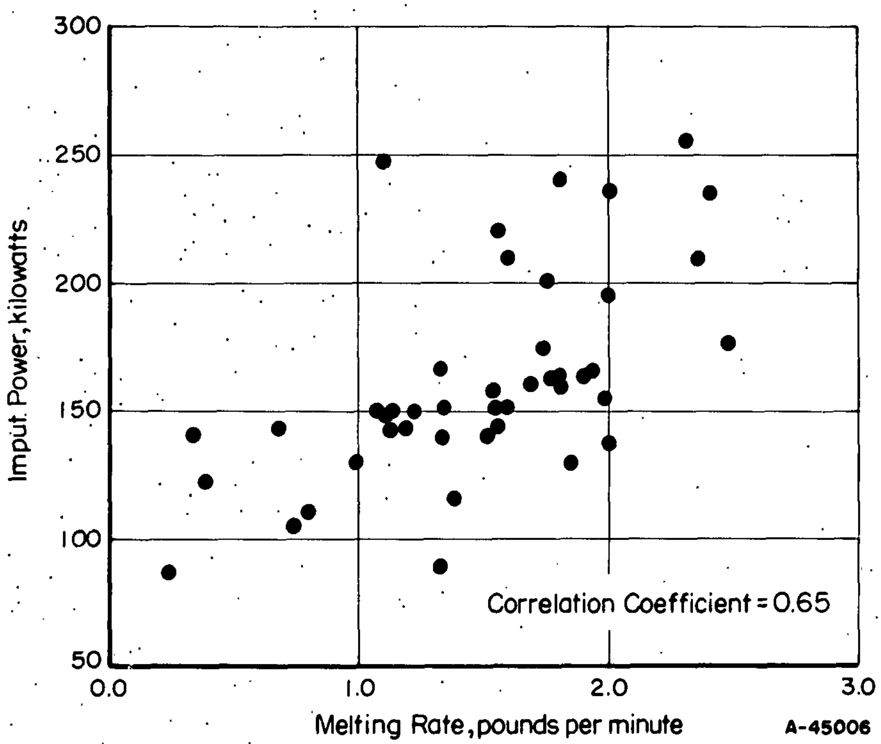

FIGURE 1. SCATTER DIAGRAM FROM THE ATTEMPT TO RELATE INPUT POWER TO THE CONSUMABLE ELECTRODE MELTING RATE

parameter to include the influence of the ingot and electrode cross-sectional areas and the electrode density. The relative importance of each of these variables in terms of how they affect the melting process is, briefly discussed, as follows:

> Being in direct contact with the arc, the ingot and electrode cross-sectional areas represent the total surface areas available for heat loss by conduction and radiation. Therefore, since melting rate is dependent on heat concentration, higher melting rates would be expected at a given power level with smaller combinations of cross-sectional area, i.e.,
>
> $$(D_e^2 + D_i^2) .$$
>
> In this same respect, electrode density (per cent of theoretical) would also be expected to influence melting rate. For a given electrode diameter, the effective cross-sectional area depends on density, with low-density material presenting less surface area to the arc than high-density material. Higher melting rates would then result using low-density electrodes since less surface area would be available for heat conduction.
>
> As suggested by Butler and Morgan(5) and Noesen and Hughes(6), the melting rate at a given power level is extremely sensitive to changes in the electrode density. Lower densities correspond to higher electrode resistivity and reduced thermal conductivity. Both of these changes in electrode properties act to raise the temperature of the electrode tip, hence increasing the melting rate.

From the above discussion it is clear that any melting-rate parameter showing a high degree of correlation with input power would have to allow for the effects of (1) electrode density and (2) ingot and electrode surface areas. As indicated in Table 2, a parameter of this type was developed. Essentially this was accomplished by evaluating various empirically formulated products of melting rate, electrode density, and the ingot and electrode cross-sectional areas with respect to their ability to correlate with input power.

First, only the influence of cross-sectional area, proportional to

$$(D_e^2 + D_i^2),$$

was considered. As shown in Table 2, this was achieved by calculating a series of correlation coefficients for input power versus the product

$$R(XD_e^2 + YD_i^2).$$

TABLE 2. SUMMARY OF CORRELATION COEFFICIENTS CALCULATED TO SHOW THE RELATIONSHIP BETWEEN INPUT POWER AND VARIOUS ADJUSTED MELTING-RATE PARAMETERS

Adjusted Melting-Rate Parameter	Correlation Coefficient, r	
$R(0.0D_e^2 + 1.0D_i^2)$	0.813	
$R\rho(0.0D_e^2 + 1.0D_i^2)$		0.824
$R(0.2D_e^2 + 0.8D_i^2)$	0.820	
$R\rho(0.2D_e^2 + 0.8D_i^2)$		0.833
$R(0.5D_e^2 + 0.5D_i^2)$	0.841	
$R\rho(0.5D_e^2 + 0.5D_i^2)$		0.850
$R(0.7D_e^2 + 0.3D_i^2)$	0.860	
$R\rho(0.7D_e^2 + 0.3D_i^2)$		0.873
$R(0.8D_e^2 + 0.2D_i^2)$	0.873	
$R\rho(0.8D_e^2 + 0.2D_i^2)$		0.888
$R(0.9D_e^2 + 0.1D_i^2)$	0.881	
$R\rho(0.9D_e^2 + 0.1D_i^2)$		0.876
$R(1.0D_e^2 + 0.0D_i^2)$	0.857	
$R\rho(1.0D_e^2 + 0.0D_i^2)$		0.855

In this parameter, X and Y represent weighting factors $(X + Y = 1)$ incorporated to assess the relative importance of

$$D_e^2 \text{ and } D_i^2$$

in optimizing the correlation. The result of this initial effort in terms of the correlation coefficients for various ratios of the weighting factors is shown in Figure 2. Correlation coefficients of 0.813 and 0.857 were obtained for $X = 0$ and $Y = 0$, respectively, while a maximum value of 0.881 was obtained for $X = 0.9$, i.e.,

$$R(0.9D_e^2 + 0.1D_i^2).$$

Attempting to obtain an even higher degree of correlation, a similar series of calculations was performed to evaluate the significance of electrode density, ρ. This was accomplished, as shown in Table 2, by calculating correlation coefficients for input power versus the parameter

$$R\rho\ (XD_e^2 + YD_i^2).$$

A comparison of the correlation coefficients obtained using this parameter with those obtained from its counterpart without the density term is also illustrated in Figure 2. The general shapes of the curves in this figure are similar for both parameters, and the maximum or optimum correlation coefficient, 0.888, resulted for the density-compensated parameter,

$$R\rho\ (0.8D_e^2 + 0.2D_i^2).$$

The plot of the optimum adjusted melting-rate parameter versus input power is shown in Figure 3. Generally, this figure interrelates the five basic arc-melting variables according to the formula

$$P = 10\ R\rho\ (0.8D_e^2 + 0.2D_i^2) + 100,$$

where

P = input power, kilowatts

R = melting rate, pounds per minute

ρ = electrode density, fraction of theoretical

D_e = diameter of electrode, inches

D_i = diameter of ingot, inches

Considering the effect of melting point on the relation shown in Figure 3, distinction was made between those materials containing 92 to 95 and 95 to 100 per cent tungsten. Although a melting-point effect is not definitely reflected in this plot, i.e., higher power levels being required

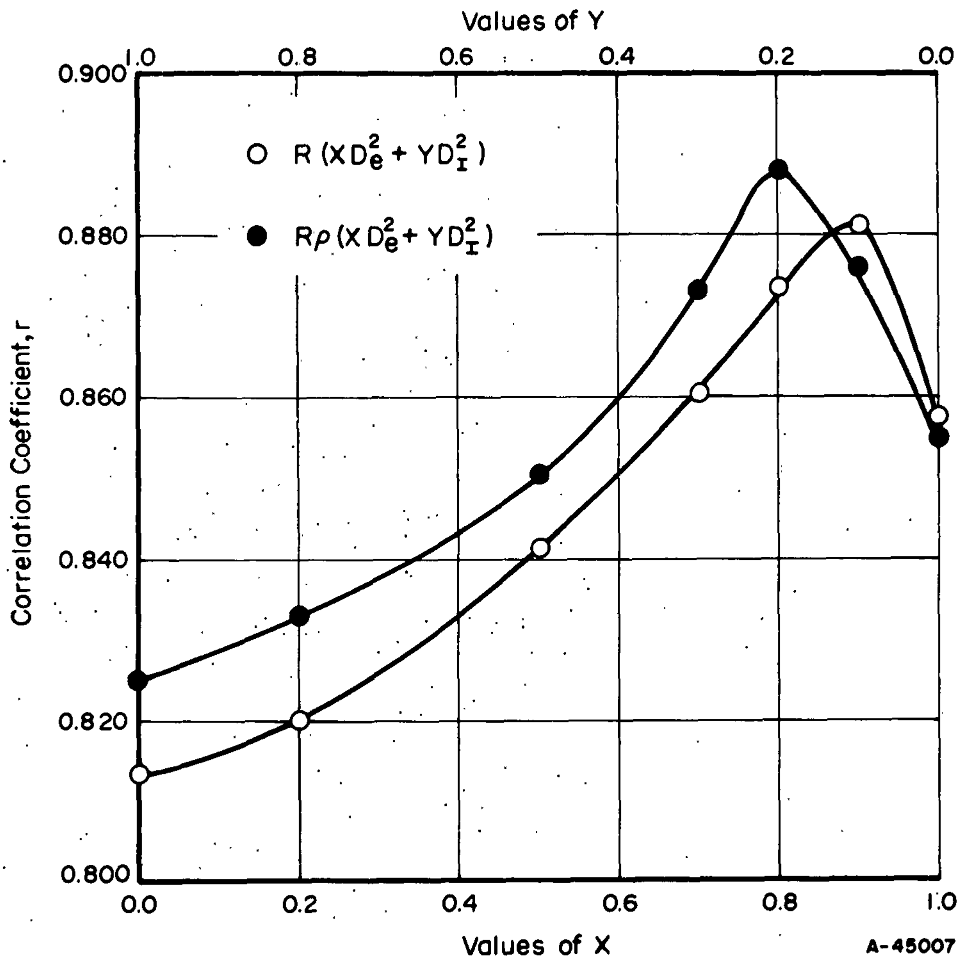

FIGURE 2. INFLUENCE OF THE WEIGHTING FACTORS, X & Y, IN ACHIEVING AN OPTIMIZED ADJUSTED MELTING RATE PARAMETER

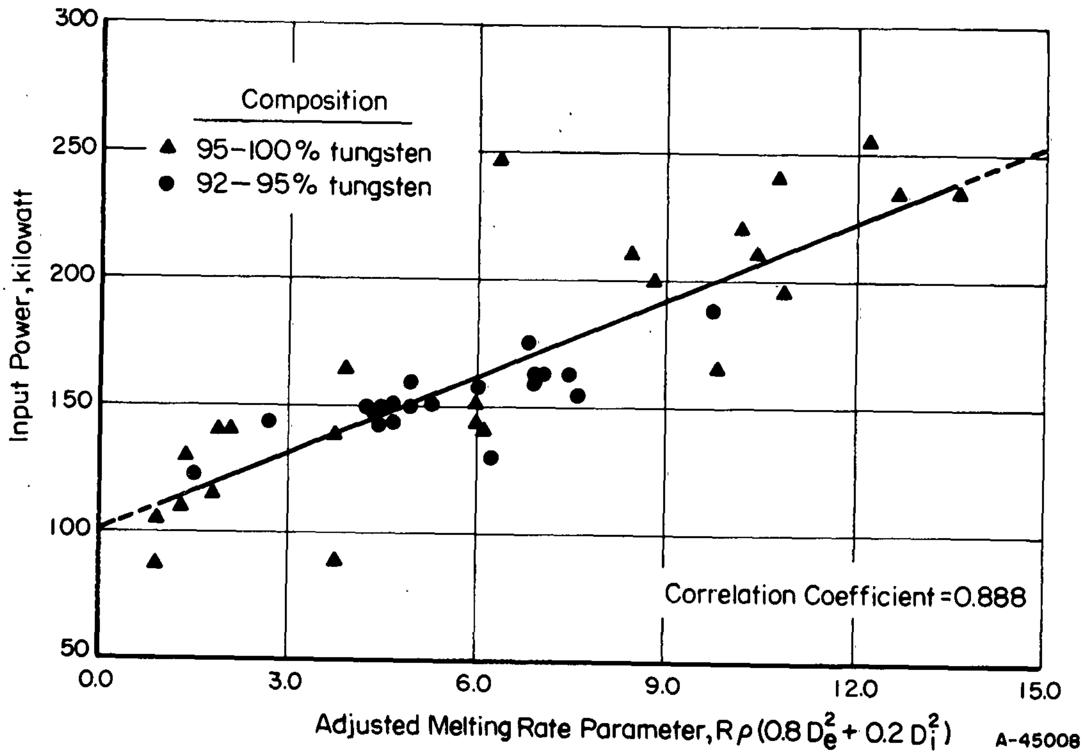

FIGURE 3. OPTIMIZED LINEAR RELATIONSHIP BETWEEN INPUT POWER AND THE ADJUSTED MELTING RATE PARAMETER

to melt the 95 to 100 per cent tungsten category than the 92 to 95 per cent category, it seems safe to assume that a degree of correlation higher than 0.888 would have been achieved if sufficient data from a single .aterial had been available for the analysis.

DISCUSSION AND CONCLUSIONS

From the above relation, it is apparent that input power is directly related to melting rate, electrode density, and a weighted sum of the ingot and electrode cross-sectional areas. Concerning the last factor, it is important to note that the optimum correlation (see Figure 2) is obtained by considering 80 and 20 per cent of the electrode and ingot cross-sectional areas, respectively. This result is significant as it indicates the melting rate, R, to be more sensitive to changes in the electrode diameter than to equivalent changes in the ingot diameter.

Of further significance is the fact that data from seven different sources were represented in the analysis. From this it can be concluded that existing differences between the melting practices and furnace designs have little or no effect on the correlation among the variables from the several sources. A higher degree of correlation, however, might have been expected had sufficient data from a single source and single alloy composition been available for the analysis.

Further technological and economic ramifications from the relationship developed in this memorandum can be realized from the following example calculations:

(1) How much power is required to cast a 6-inch-diameter ingot of unalloyed tungsten at a melting rate of 1.5 pounds per minute using a 2.70-inch-diameter, 92 per cent dense, electrode?

$$P = 10 \times 1.5 \times 0.92\ (0.8 \times 2.70^2 + 0.2 \times 6.00^2) + 100$$

$$P = 10 \times 17.60 + 100 = \underline{276\ \text{kw}}$$

(2) With 225 kw of power available and using an electrode/crucible diameter ratio of 0.45, what is the maximum diameter ingot of unalloyed tungsten that could be cast while melting at the rate of 1.0 lb/min?

$$225 = 10 \times 1.0 \times \rho\,[0.8\ (0.45D_i)^2 + 0.2D_i^2] + 100$$

$$225 = 10 \times \rho \times 0.36D_i^2 + 100$$

$$D_i^2 = \frac{35}{\rho}$$

From this point, the final solution to the problem depends on the selection of electrode density, as shown in Figure 4. For densities ranging between 100 and 80 per cent of theoretical, ingots ranging in diameter from 5.82 to 6.51 inches may be cast.

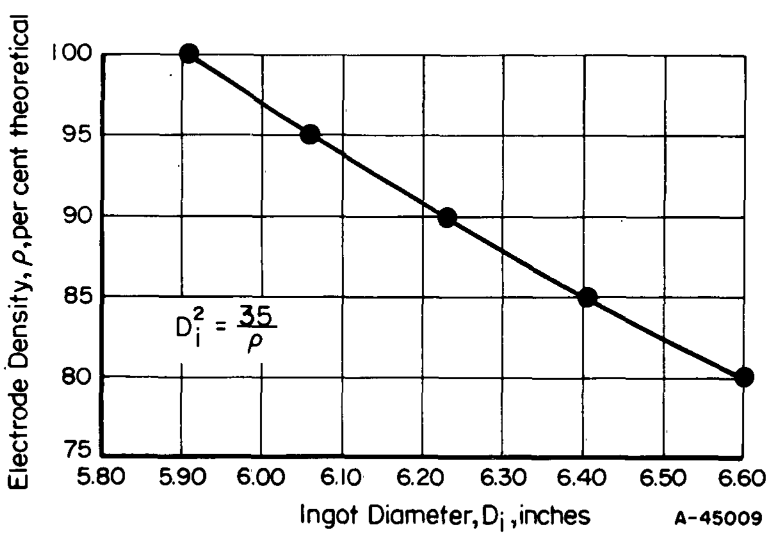

FIGURE 4. RELATIONSHIP BETWEEN INGOT DIAMETER AND ELECTRODE DENSITY FOR EXAMPLE CALCULATION NO. 2

In conclusion, the general significance of the relationship developed here may be summarized as follows:

(1) A known relation among the arc-melting variables would aid current efforts to optimize tungsten-base-alloy arc-melting practices.

(2) With arc-melting practices eventually optimized, use of the relationship would contribute to consistency among these practices and hence to quality control in the production of tungsten-base-alloy ingots.

(3) A relationship similar to the one developed here might also be expected to apply equally as well in defining the arc-melting process for other metals.

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(6) Noesen, S. J., and Hughes, J. R., "Arc Melting and Fabrication of Tungsten", Trans. AIME, Vol. 218, pp 256-261 (April, 1960).

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LIST OF DMIC MEMORANDA ISSUED
(Continued)

A list of DMIC Memoranda 1-164 may be obtained from DMIC, or see previously issued memoranda.

DMIC Memorandum Number	Title
165	Review of Uses for Depleted Uranium and Nonenergy Uses for Natural Uranium, February 1, 1963
166	Literature Survey on the Effect of Sonic and Ultrasonic Vibrations in Controlling Grain Size During Solidification of Steel Ingots and Weldments, May 15, 1963
167	Notes on Large-Size Furnaces for Heat Treating Metal Assemblies, May 24, 1963 (A Revision of DMIC Memo 63)